Data Assimilation in Shelf Circulation Models

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LONG-TERM GOALS

The goal of this research project is to develop data assimilation (DA) methods for coastal circulation models and to apply these methods to measurements from the Oregon shelf. We envision the development of an optimal, versatile, and relocatable DA system based on a primitive equation model with a turbulence submodel. The planned system could be used efficiently both for operational needs (forecasting, search and rescue, environmental response) and for fundamental studies of coastal ocean dynamics.

OBJECTIVES

The immediate scientific objectives of this research project are to develop practical, but still nearly optimal methods for the assimilation of data into coastal circulation models, and to apply these methods to time-series measurements from moorings and coastally-based high frequency (HF) standard and long range radars, satellite data (SSH, SST), and hydrographic survey data (e.g., from autonomous underwater vehicles, AUVs, and gliders). An important additional scientific objective is to utilize data assimilation to study the physics of coastal ocean circulation processes, for instance, to understand the zones of influence of assimilated observations, covariability of processes over the shelf, in the coastal transition zone (CTZ), and in the adjacent interior ocean and to provide information on the magnitude and spatial and temporal structure of errors in model forcing.

APPROACH

The proposed research involves a systematic continuation of work in progress that has included assimilation of current measurements from both moored instruments and an array of HF radars deployed along the Oregon coast. Additional data types, including satellite SST and SSH and in-situ

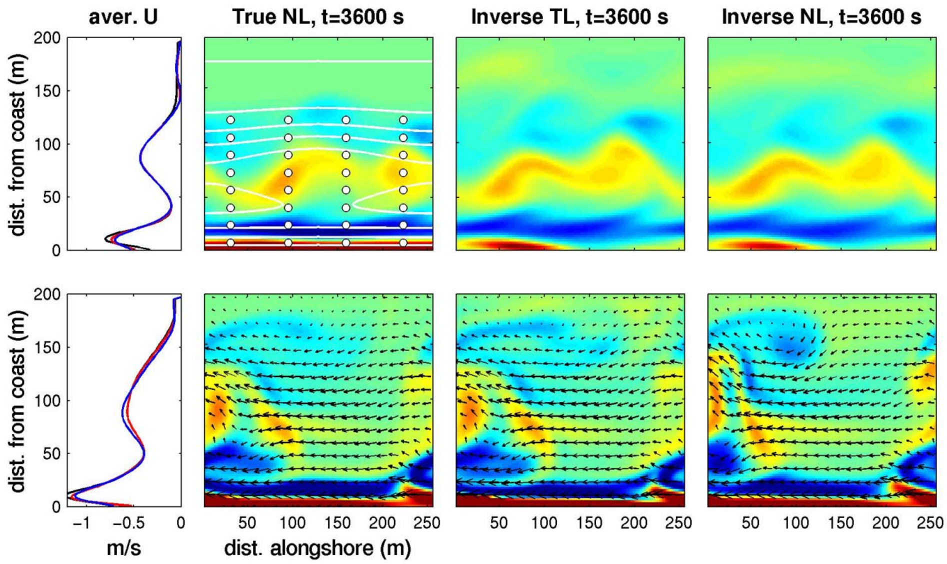

Figure 1. [Our data assimilation system has been tested in an equilibrated wave regime (top plots) and a more strongly nonlinear, irregular regime (bottom plots). In each case, time-series of synthetic data (surface elevation and velocity) were assimilated at the locations shown as circles. Plots on the left are the time- and alongshore-averaged alongshore current of the true nonlinear solution (black), the inverse tangent linear solution (blue), and inverse nonlinear solution forced by the corrected (inverse) forcing (red). Color maps show snapshots of vorticity (color) and velocity vectors (only in the bottom plots) from those solutions at the end of the assimilation time interval. White contours are bathymetry (every 0.5 m).]

sections of hydrographic and turbulence observations, have been used to verify the results of data assimilation. Studies of dynamics have been focused on wind-driven upwelling and internal tides on the shelf. The problem of coastal data assimilation has been approached simultaneously from two directions: (i) application of optimal, variational data assimilation schemes to simplified linear models (Scott et al. 2000, Kurapov et al. 1999, 2002, 2003) and (ii) application of simplified, sub-optimal data assimilation schemes [such as optimal interpolation (OI)] to a full primitive equation model (Oke et al. 2002, Kurapov et al. 2005a, 2005b, 2005c).

In our implemention of the OI with the nonlinear, hydrostatic, primitive equation Princeton Ocean Model (Kurapov et al. 2005a, 2005b), state variables were updated sequentially based on data-model differences and stationary estimates of forecast and data error statistics. Such a simple sequential approach improves modeled coastal ocean circulation on average over the season. However, to improve prediction on the event scale, especially in intermittent regimes (frontal meandering, coastal current separation, relaxation from upwelling to downwelling) more elaborate DA methods must be employed that rely on the time-dependent (ocean state dependent) forecast error statistics. So, recently we began approaching the merger of the two abovementioned approaches, with focus on the development and implementation of the representer-based variational DA method with nonlinear high-resolution regional models of coastal ocean dynamics, following methodology outlined by Chua and Bennett (2001). The representer-based method approaches the nonlinear optimization problem as a

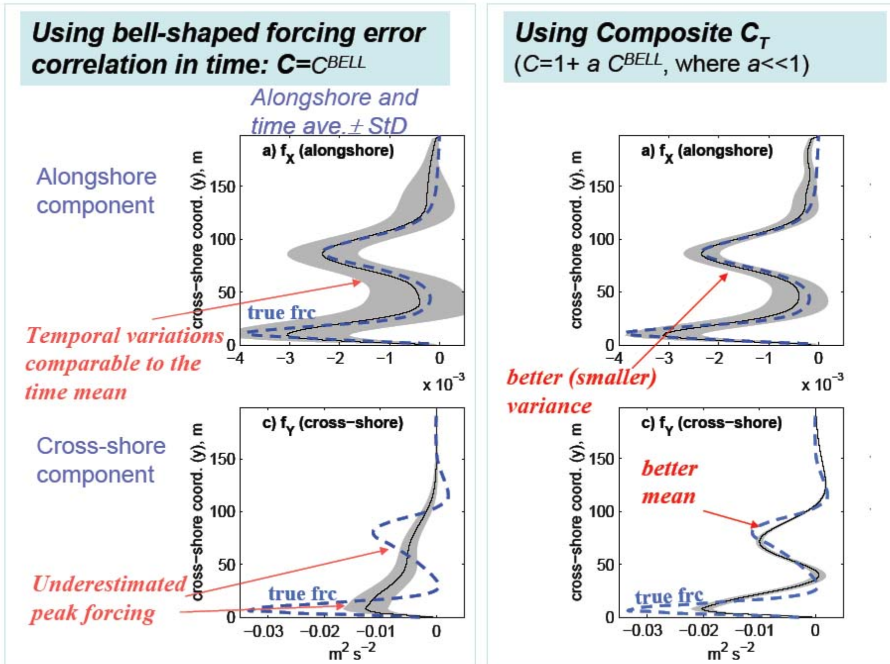

Figure 2. [Using a more advanced forcing error covariance allowed obtaining a more accurate estimate of the true time-invariant forcing (right) than in case using a more traditional covariance (left). The dashed line is the alongshore average of the true forcing, alongshore (top) and cross-shore (bottom) components; solid lines and shaded areas show the alongshore averages of the inverse estimates of the forcing ± temporal standard deviation.]

series of linearized optimization problems, each solved efficiently in the data subspace of the state space. This approach allows substantial flexibility in the choice of assumed error covariances. The resulting optimal solution can be viewed as an objective mapping of the assimilated observations utilizing covariances (mapping rules) that depend on the background nonlinear ocean state. The method is economical in that the model state error covariance (a very large matrix) is not computed explicitly. Utilizing the indirect represetenter algorithm (Egbert et al. 1994) as a linear solver, the method is applicable with large data sets. As for any variational method, the representer method requires repeated solution of the tangent linear and adjoint systems corresponding to the nonlinear dynamical model.

Instabilities and eddy interactions are common features in the highly energetic coastal ocean environment. Instability growth is constrained in a nonlinear model as a result of energy cascades. However, such a mechanism would not be necessarily present in the tangent linear model, and so exponential growth of instabilities possibly may pose a threat to convergence of an iterative optimization algorithm based on linearization. As a first step in addressing this issue, we have implemented the representer method for the shallow-water model of circulation in the nearshore surf zone (Kurapov et al. 2007). This idealized study has given us useful experience on many nontrivial details of the representer approach (such as formulation of input and output states; the proper adjoint for time-continuous forcing; preconditioning of the minimization algorithm). Encouraged by the success with that model (see below), we are now implementing a similar approach for a model of three-dimensional stratified flows. The nonlinear dynamics is based on the Regional Ocean Modeling System (ROMS, Haidvogel et al. 2000). The tangent linear and adjoint ROMS codes (Moore et al.

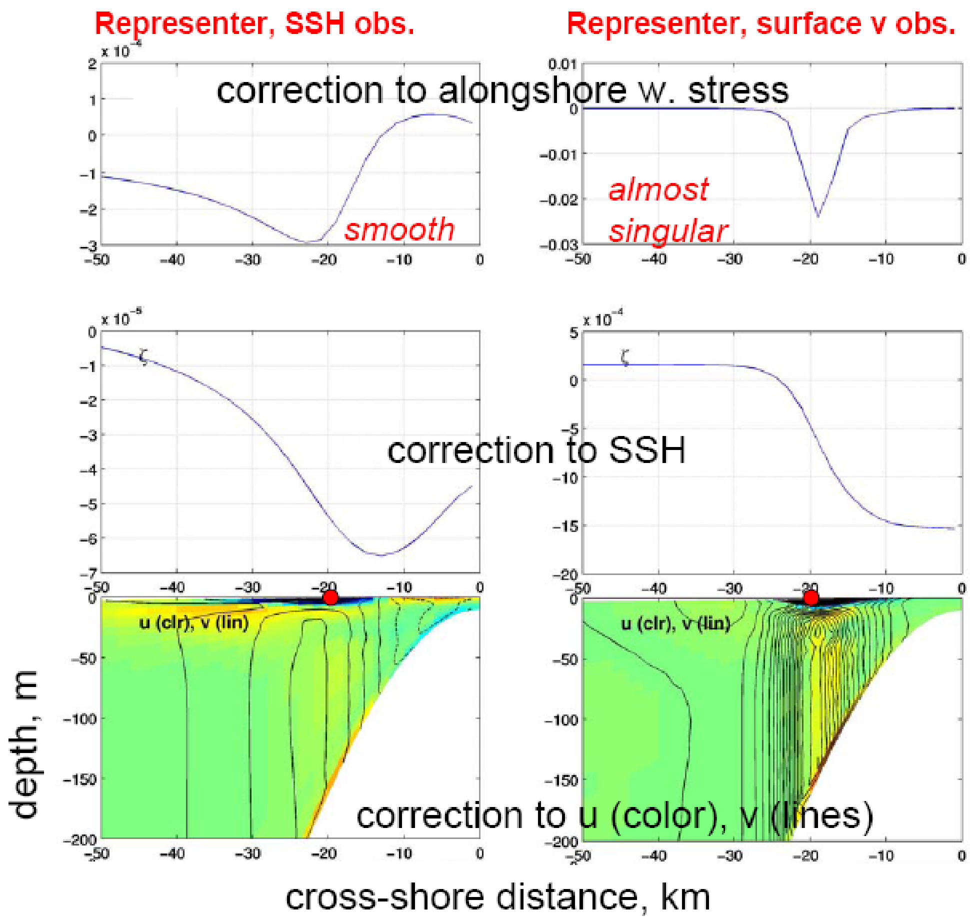

Figure 3. [Representers for the observation of SSH (left) and surface alongshore velocity component (right) show that these observation will have different impacts on assimilation in the coastal area. The representers are computed in the idealized setting (along-shore uniform problem, no perturbation to temperature and salinity), for the case of upwelling background conditions. They are shown in cross-shore sections at the time of observation: wind stress (top), SSH (middle), and two components of horizontal velocity (bottom), the cross-shore component as color and alongshore component as line contours.]

2004, Di Lorenzo et al. 2007) were released to the research community in February 2007, providing new opportunities for variational DA in the coastal area. The emergence of the Inverse Ocean Modeling System (IOM), a modular computer interface for representer-based computations developed by Prof. A. Bennett (OSU) and associates, can also help in the implementation of variational DA.

Along with the development of DA methodology, we have continued to advance our 3D stratified model for the Oregon shelf flows, testing limited-area versions of ROMS with open boundary conditions suitable for the energetic coastal flows off Oregon, studying possible interactions of wind- and tidally-driven baroclinic flows, as well as the effects of the Columbia River on the upwelling dynamics off Oregon. Model improvements resulting from those tests will provide better physical compatibility between assimilated data and the model.

WORK COMPLETED

Our efforts over the current project period have involved four tasks, all relevant to our objective of developing a representer-based DA system for Oregon shelf and CTZ flows: (1) development of all components required to implement the representer scheme for the shallow-water equations, and successful application of these components to a challenging nonlinear problem, (2) gaining experience with ROMS tangent linear and adjoint codes, including tests of a cycling representer algorithm with real data, (3) development of a modified version of the ROMS codes to extend their capabilities in the coastal region and to simplify implementation of the representer approach, and (4) continued development and application of our model to the Oregon coast.

The study of the utility of the representer method with a nonlinear shallow water model of nearshore flows, focused on the eddy regimes, has been completed, and a paper has been accepted for publication at the Journal of Geophysical Research (Kurapov et al. 2007; the draft is available online at ftp://ftp.coas.oregonstate.edu/dist/kurapov/pub/kurapov_JGR_2007JC004117.pdf). The nearshore DA system used for this study utilized tangent linear and adjoint codes developed by the PI at OSU. It was applied to synthetic data assimilation experiments in a problem of alongshore flow over variable beach topography driven by gradients of radiation stresses from breaking waves in the surf zone (Slinn, Allen, and Holman, 2000). In our study, the true forcing was spatially variable, but time-invariant. Depending on the magnitude of the bottom friction parameter, the alongshore flow may exhibit shear instabilities that result in regular equilibrated wave patterns in a weakly nonlinear regime, or irregular "turbulent" behavior in a weakly frictional and more strongly nonlinear regime (Figure 1). Using a periodic channel set-up, we have run successful experiments in both regimes. The data were sampled from a "true" fully developed unsteady nonlinear solution that featured an alongshore current in excess of 1 m/s and intensive eddy variability. The prior initial conditions and forcing were zero; hence, all the information about the flow and forcing was extracted from the data. The goal of DA was to obtain improved estimates of both the initial conditions and the forcing that would, in turn, yield a dynamically balanced nonlinear solution fitting the data. Our goal was to predict eddies deterministically over much larger time intervals (up to 1 h) than the characteristic time scale of meanders and eddies (5-10 min). Experiments with different forcing error covariances were run to study the effects of covariance assumptions on the convergence and accuracy of the iterative algorithm.

On the path to utilizing the representer method with a model of three-dimensional coastal circulation, we have been testing ROMS tangent linear and adjoint codes. These codes have so far been implemented to correct model error due to initial conditions (e.g., Di Lorenzo et al. 2007). Our testing involved the analysis of representer solutions that can be obtained with one adjoint and one tangent linear run and show patterns of the correction corresponding to a single observation. We have also done initial tests assimilating long-range HF radar observations near cape Blanco in attempts to improve the timing and extent of westward current separation using observations for summer 2002. In those tests, utilizing representer cycling (Xu and Daley, 2002), assimilation proceeded in a series of 2-day time windows, each time followed by a 2-day forecast. In each window, initial conditions were corrected. The minimization algorithm was re-written for the special case, in which the correction was projected on dominant multivariate empirical orthogonal functions (EOFs), obtained from the prior solution. Such an approach could provide an economical way of minimization since the correction would have a small number of degrees of freedom (in fact, the adjoint model would not be needed, only the tangent linear model). Further research is necessary to assess the utility of this approach.

To resolve some of the deficiencies of the existing tangent linear and adjoint ROMS codes, we have been working on modified versions that allow: (i) correction of time-continuous atmospheric forcing and dynamical errors (the impulsive (in time) forcing correction implemented in the existing standard ROMS codes excites large amplitude transients that dominate the low frequency balances such as geostrophy); and (ii) assimilation of more general data types than is currently allowed in the standard ROMS (esp., low-pass filtered data that can be used to minimize transients as a result of initial condition correction; demeaned alongtrack SSH; HF radar radial components, which are combinations of the two orthogonal components). In this work, we have developed, coded, and tested an adjoint algorithm that is strictly consistent with time-interpolation of the forcing in the nonlinear and tangent linear codes. Note that a capability to correct wind stress may be necessary to account for the error in the atmospheric forcing prediction due to the atmosphere-ocean interactions over the cold upwelling front (N. Perlin et al. 2007, Chelton et al. 2007). Our modified code allows inhibiting high frequency transients in the representer solutions when errors in the forcing are corrected. A similar algorithm can be applied to the dynamical errors on the r.h.s. of the model equations, which may be necessary in the future to provide means of time-continuous control of baroclinic instabilities. With our modification to the observation representation in the DA system, any linear combination of data can be assimilated without further need to add to the tangent linear and adjoint codes. The abovementioned modifications have produced codes that are more consistent with the IOM system. Using our modified system, representers have been analyzed in an idealized coastal setting (cross-shore sections, no perturbation in the temperature and salinity) to verify dynamical consistency in the correction fields.

We have also continued testing the nonlinear Oregon coastal ocean model, in collaboration with Dr. S. Springer (supported by NOPP), Dr. B. J. Choi (supported by GLOBEC), and D. Fulton (an NSF-REU summer intern). The model is based on ROMS with 3-km horizontal resolution, spanning between 41N and 47N in the alongshore direction and 300 km in the offshore direction. The boundary conditions are obtained by nesting in the NCOM regional model of California Current System (NCOM solutions have been provided by J. Kindle, NRL). In particular, we have advanced our model to include the Columbia River discharge and then conducted studies to determine how the plume affects dynamics of upwelling.

RESULTS

In our study with the shallow water model of nearshore circulation, we demonstrated that the representer method can yield a convergent and accurate solution in a 1-hour window, substantially longer than the dominant eddy time scale (several minutes). That result was achieved both in the weakly and strongly nonlinear regimes. In a weakly nonlinear (equilibrated waves) regime, using a forcing error covariance **C** that allows only a steady forcing correction yields a convergent and accurate solution. In the strongly nonlinear (irregular) regime, the DA system cannot find sufficient degrees of freedom with steady forcing to control eddy variability. Implementing a bell-shaped temporal correlation function in **C** with the 1-min decorrelation scale yields a convergent linearized inverse solution that describes correctly the spatio-temporal variability in the eddy field. The corresponding estimate of forcing, however, is not satisfactory. Accurate estimates of both the flow and the forcing can be achieved by implementing a composite **C** with a temporal correlation separated into order 1 steady, and relatively smaller amplitude time-variable parts (Figure 2).

Representer analyses performed in the cross-shore section, using our modified version of ROMS tangent linear and adjoint codes, have illustrated that observations of SSH and alongshore surface velocity have different zones of spatial influence in the cross-shore direction (Figure 3). For instance,

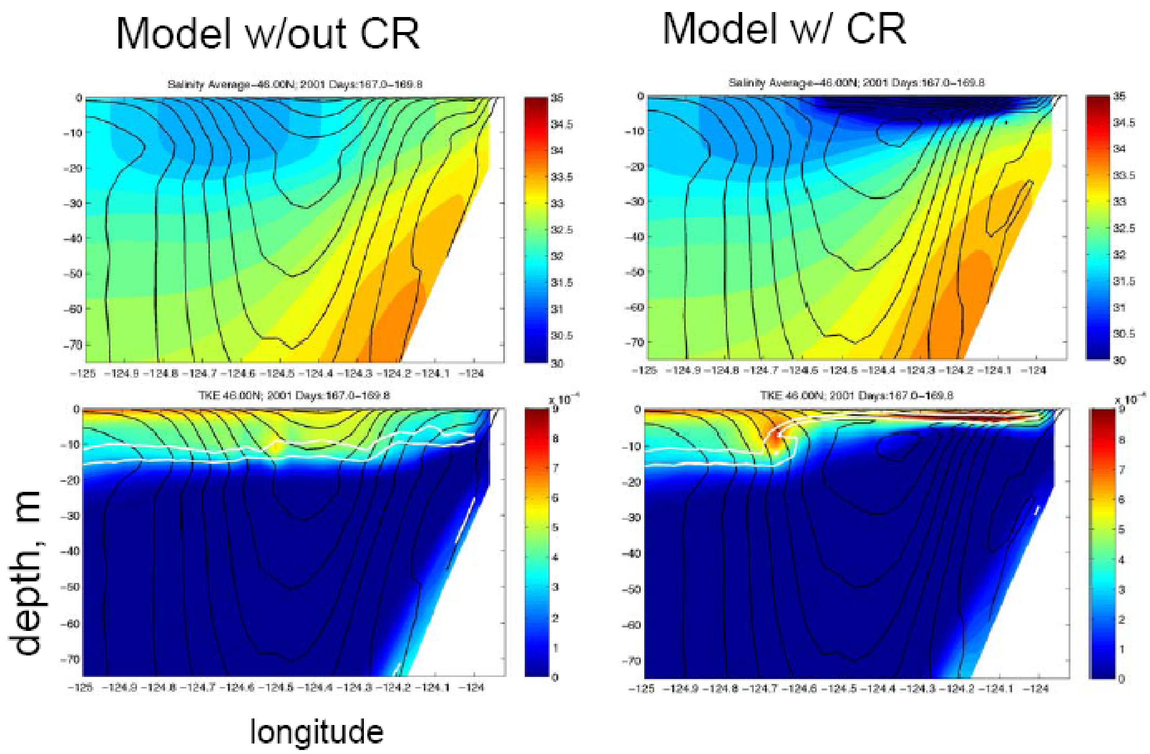

Figure 4. [ROMS solutions in cross-sections at 46N, 20 km south of the Columbia River, show that in case with the river plume (right) the thickness of surface boundary layer can be one third of the that in the case without the river plume (left); the turbulent kinetic energy in the surface boundary layer is increased in the case with the plume. Shown as color are the salinity, psu (top) and turbulent kinetic energy, m^2/s^2 (bottom). In each plot the black line contours are the alongshore velocity, every 5 cm/s. The white contours in bottom plots those of constant Richardson number (0.25 and 1).]

if in the process of DA it is assumed that model errors are due to those in the wind stress and a small decorrelation scale is assumed in the cross-shore direction, an observation of SSH would contribute to correction in the wind stress and velocity fields on a large scale, on the order of a barolcinic Rossby radius of deformation (Figure 3a). In contrast, the representer corresponding to an observation of the alonghsore surface velocity component (*v*) is almost singular in the cross-shore direction, indicating a very local correction (Figure 3b). More generally, the scale of correction due to assimilation of surface *v* will be determined by the cross-shore scale of the assumed forcing error covariance. In both cases (see Figures 3a and b), the correction fields are dynamically balanced (for instance, geostrophy is nearly maintained between the pressure gradient and alongshore velocity corrections away from the boundary layers, and corrections in the wind stress and near-surface cross-shore velocity component are in Ekman balance). This balance is not implied by the choice of the covariance, as in OI, but is rather a result of propagating the error in the wind stress through the tangent linear model.

Verifications of the nonlinear CTZ model against available shelf mooring observations have shown that the model, nested into NCOM, is accurate on the shelf for the entire summer upwelling period (April-September). This model also describes qualitatively correctly the cross-shore extent of coastal current separation off Heceta Bank (44.2N) and Cape Blanco (43N), as verified by comparison with AVISO alongtrack SSH altimetry. The location and timing of eddies in the separation area off Cape

Blanco are sensitive to details of model formulation (Springer, pers. comm.). It is anticipated that assimilation (esp., of HF radar and SSH altimetry) will improve predictions.

The model study of the Columbia River influences on the Oregon shelf has shown that in the area between 45 and 46N in May-June the inclusion of river discharge improves substantially the near-surface stratification. Increased stratification at the base of the plume will tend to decrease turbulence production. At the same time, the increased horizontal density gradient introduced by the plume will cause the increase the vertical shear in horizontal velocities by thermal wind balance. The net effect of the plume is a thinner surface boundary layer, in which the turbulent kinetic energy is increased (Figure 4). Since the Ekman transport is distributed in a thinner boundary layer, the surface cross-shore velocities can be 3 times as large in the plume than away from it (Kurapov et al., manuscript in prep.).

IMPACT/APPLICATIONS

Studies with the shallow water model have delivered important information on the utility of variational data assimilation in a strongly nonlinear flow regime, providing guidance for more computationally and dynamically challenging 3D cases. Due to advances in the formulation of the hypotheses about errors in dynamical equations (the weak-constraint approach), variational data assimilation can be implemented successfully over periods of time that are substantially larger than the time scales characteristic of instability growth. Representer analyses using our modified version of the tangent linear and adjoint ROMS codes have provided information on the zones of influence of the surface observations, such as SSH altimetry and HF radar surface velocities. Modeling studies with the nonlinear ROMS have demonstrated that the Columbia River plume affects the upwelling and cross-shore transport over the Oregon shelf and has to be included in the prediction model.

TRANSITIONS

Our latest advances in modeling the Oregon shelf flows have been incorporated into a pilot real-time forecast model (supported by NOAA) that has produced daily updates of three-day ocean forecasts. The forecast graphics have been posted online at http://www-hce.coas.oregonstate.edu/~orcoss/SSCforecast.html, as well as on the pages of the Oregon Coastal Ocean Observing System (OrCOOS) (www.orcoos.org). The OSU glider group (Barth, Shearman) has utilized these forecasts to guide deployment of gliders. Prof. Levine (OSU) has proposed to ONR to utilize those forecasts for guidance in the dye release experiments on the Oregon shelf.

RELATED PROJECTS

Progress on variational data assimilation through this project will directly benefit the research in two projects: (1) “Effects of meso- and basin scale variability on zooplankton populations in the California Current System using data-assimilative, physical/ecosystem models”, US-GLOBEC-NEP, NOAA and (2) “Boundary conditions, data assimilation, and predictability in coastal ocean models”, ONR-NOPP.

A Ph.D. student John Osrborne has begun working with us this fall, supported by the NSF grant on “Modeling and Assimilation of Internal Tides in Interaction with Subinertial Wind-Forced Flows in the Coastal Ocean” (PI: Kurapov, co-PI: Egbert). On this project, we will build and analyze the outputs of the Oregon shelf model at a higher resolution (<1 km in horizontal) and will include tidal forcing. This model will eventually be nested in our 3-km data assimilative real-time product. The tangent linear and adjoint codes that we are testing now will be utilized to assimilate long-range HF radar data in the tidal frequency band.

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